Biomethane as Transport Fuel

A Study on Upgrading Technologies and Biomethane Potential in Finland

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Abstract

Due to the negative environmental impact caused by fossil fuels usage, the focus on bioenergy has been raised in recent years. Biogas produced from an anaerobic process is good enough to produce electricity and heat, but after upgrading to biomethane, it also has a great potential to act as vehicle fuel. This Bachelor's thesis starts with a theoretical background of the benefits of using biomethane as transport fuel. It reviews and compares five current upgrading technologies: membrane separation, pressure swing adsorption (PSA), water scrubber, chemical scrubber and organic physical scrubber. A comparison between them is summarized. In addition, Finnish biomethane status quo is studied: the locations of nine upgrading plants in Finland and a map of all the filling stations are shown. The thesis also reviews EU and national policies and targets on biomethane, in order to promote the utilization of it.

The result of the work is that you get an idea of biomethane as transport fuel and how it can benefit the future climate. As for biogas plants that are interested in constructing a new upgrading unit, this thesis will provide reference material for decision makers.

Language: English Key words: biomethane, transport fuel, upgrading technologies, bioenergy

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Abstarkt

På grund av den negativa miljöpåverkan som användningen av fossila bränslen orsakar, har fokuset gentemot bioenenergi höjts under de senaste åren. Biogas som producerats genom en anaerob process kan användas både till att producera elektricitet och värme, och efter en uppgradering till biometan har biogasen också en stor potential att användas som fordonsbränsle.

Det här ingenjörsarbetet behandlar först en teoretisk bakgrund gällande fördelarna med att använda biometan som fordonsbränsle. I arbetet gås fem olika uppgraderingsmetoder igenom och jämförs. Metoderna är: membran separation, PSA, absorption i vatten, kemisk adsorption och organisk fysisk adsorption. En jämförelse mellan dessa är sammanställd. Dessutom har Finlands biometans status quo undersökts; positionen av nio uppgraderingsanläggningar i Finland samt en karta av alla tankstationer är markerade. Ingenjörsarbetet granskar också EU:s och nationella policyer och mål gällande biometan, med syftet att främja användningen av den.

Resultatet av ingenjörsarbetet är att det ger läsaren en bild av biometan som fordonsbränsle och hur det framtida klimatet kan ha nytta av den. Även biogasanläggningar som är intresserade av att konstruera en ny uppgraderingsenhet kan dra nytta av detta arbete som referensmaterial.

Språk: Engelska Nyckelord: biometan, fordonsbränsle, uppgraderings-metoder, bioenergi

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Explanation of Terminology and Abbreviations

AD	Anaerobic digestion
BEV	Battery electric vehicle
BtL	Biomass-to-liquid
CBG	Compressed biogas
CMG	Compressed methane gas
CNG	Compressed natural gas
CtL	Coal-to-liquid
EEA	the European Environmental Agency
ERTAC	the European Road and Research Advisory Council
EU ETS	The EU Emissions Trading Systems
GHG	Greenhouse gas
GtL	Gas-to-liquid
HFC	Hydrogen fuel cell
HRT	Hydraulic retention time
HVO	Hydrotreated vegetable oils
Koe	Kilos oil equivalent
LBG	Liquefied biogas
LHV	Lower heating values
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
Mtoe	Million tonnes oil equivalent
NG	Natural gas
PJ	Petajoule
PSA	Pressure Swing Adsorption
RES	Renewable energy sources

RTO	Regenerative Thermal Oxidation
Toe	Tonnes oil equivalent
TWh	Terawatt-hours
VFA	Volatile fatty acids

1 Introduction

The world is now facing huge challenges from conventional fossil fuel shortage and environmental degradation. To overcome these problems, the interest in renewable energy resources is raised and the need to produce energy from these resources is enhanced. Biogas, or biomethane, which can be upgraded from biogas, is one of many possibilities.

In order to gain more knowledge of biomethane and its utilization, this topic is selected for this bachelor's thesis. The ultimate goal is to provide a reference material to those interested parties such as biogas plants, who are still in a start-up or developing phase and to promote the use of biomethane in Finland, especially for transportation purpose.

1.1 Background

Over the past decades natural gas has become more and more important in many countries over the world. Since most EU countries do not have natural gas reserves, they are forced to import gas from other suppliers, for example Russia, the Middle East, Canada, etc. However, there is a substitute for natural gas—biomethane (Junginger, M., & Baxter, D., 2014, pp.14-15). Biogas primarily containing methane and carbon dioxide can be derived from landfill or anaerobic digestion. Its characteristics are somewhere between town gas and natural gas (IEA Bioenergy Task 24, n.d., p.4), which means it is a very valuable source of energy. The energy content of biogas is determined by the methane concentration. Biogas is upgraded to biomethane by removing carbon dioxide and other trace components, which can be used for many applications in order to reach both a maximum energy value and an environmentally friendly performance. Especially, when using biogas as transport fuel, it has to be upgraded due to the strict gas quality demands. The cleaned gas is as pure as natural gas and is suitable for all engine configurations.

The first biogas upgrading plants, according to Junginger, M., and Baxter, D., (2014, p.20), were built in the 1980s. Since then, the upgrading hasn't been developed much until 2006, when the research and development was emphasized, especially in Germany. Nowadays, there are approximately 282 biomethane plants in Europe, producing as much as 1.3 billion m^3 of biomethane annually. The upgrading technologies differ from the chemical method, the physical method, and even the biological one. Pressure swing adsorption (PSA) and water scrubber received much attention in the beginning, while the chemical scrubber has become more popular since 2009. The recent development demonstrates that membrane technology will share a larger market in the coming years (EBA, 2014). Detailed descriptions of each technology as well as a comparison are given in Chapter 4.

1.2 Method

The given task is to investigate and document upgrading technologies from biogas to biomethane. However, the first assignment, is to study the theoretical background of biogas and biomethane. This is done by reviewing a number of literature sources, with the objective of better understanding the whole process and each step separately. Then by comparing existing upgrading technologies, as well as upgrading plants in Finland, information about their sustainability, cost efficiency and possible operating challenges are gained.

The task also includes researching different materials released by authorized organizations regarding the current biomethane situation, in order to draw conclusions about its market potential and possible future development.

2 Theoretical Background

In the following subchapters, worldwide and Finnish energy use, the importance of bioenergy, biomass and its further utilization are introduced. Scientific reports are reviewed to set up this theoretical background.

2.1 Present Energy Situation

The consumption of energy is increasing rapidly due to growing population and country development. It is estimated that the energy consumption will triple from 200 quadrillion kJ in 1960 to over 600 quadrillion kJ by 2025. The bad news is that today 80% of the energy supplied is from fossil fuels and they will still be dominant in the future, although the trend has been turned to renewable energy sources. (Demirbas, A., & Demirbas, M. 2010, pp.13-14)

One type of fossil fuel, coal, is generally used to produce electricity. It provides 40% of the electricity needed in the world (International Energy Agency, 2015). The production of coal is still rising, especially in China, since this type of raw material is cheap. According to figure 1, global coal production will reach a peak in about 2025 and then start to decline.

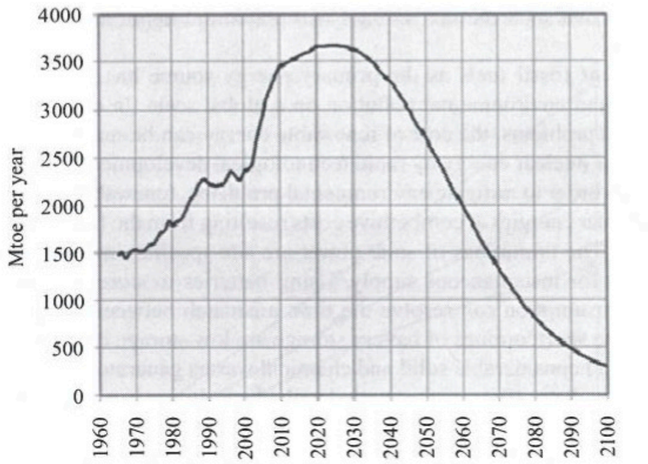

Figure 1. Global coal production (Demirbas, A., & Demirbas, M. 2010, p.15)

Another category of fossil fuel is oil, which is most in danger to become exhausted. Figure 2 illustrates global oil production scenarios based on current production and a peak is very likely going to happen around 2015. On the other hand, known oil reserves are estimated to be 2 trillion barrels (Goto, S., M. Oguma, and N. Chollacoop., 2010, p.7), of which 63% of the global reserves are controlled by the Middle East (International Energy Agency, 2015).

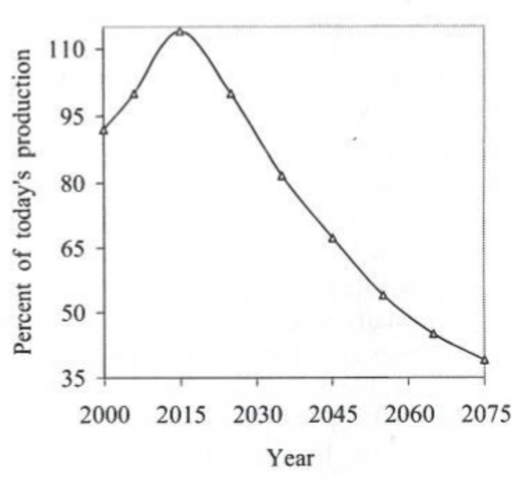

Figure 2. Global Oil Production (Demirbas, A., & Demirbas, M. 2010, p.13)

However, the problem is not the fossil fuel raw materials dying out. Real challenges exist regarding economic and environmental aspects. Dependence on oil and natural gas, especially when they are imported from other countries, can result in economic vulnerability and international tensions. Meanwhile, utilization of fossil fuels has severe impact on the environment, which has already been repeatedly discussed. (Pieprzyk, B., Kortluke, N., & Hilje, P. 2009, p. 38, pp.63-69)

Thanks to the development of modern technology, renewable energy becomes a promising alternative solution, due to its environmental-friendly feature. EU has set its "20-20-20" goal, with the renewable energy share reaching 20% of the total energy consumption by 2020. All EU countries are participating. Sweden, France and Austria are leading countries in hydropower; Germany has a significant portion of biogas production; wind energy is mainly produced in Germany, Spain and France (Country Policy Profile-Finland, 2014). Sweden and Estonia even exceeded their proposed 2020 targets already in the year 2012 (Official Statistics of Finland (OSF), 2015, p.15).

2.1.1 Energy Use in Finland

Based on a report just released by Official Statistics of Finland (OSF, 2015, p.1, p.8), the preliminary number of total energy consumption in 2014 was about 1340 petajoule (PJ), which is equivalent to 372 terawatt-hours (TWh) or 32 million tonnes oil equivalent (Mtoe). From this, 83.3 TWh is consumed as electricity. Among all kinds of energy sources, biomass is the largest source used, accounting for 24.9% in total. It is worth noticing that although the production of wind energy has quadrupled in the past five years, it only accounts for 0.003% of the total energy consumption. The share of each energy source of total energy consumption in Finland is shown in figure 3.

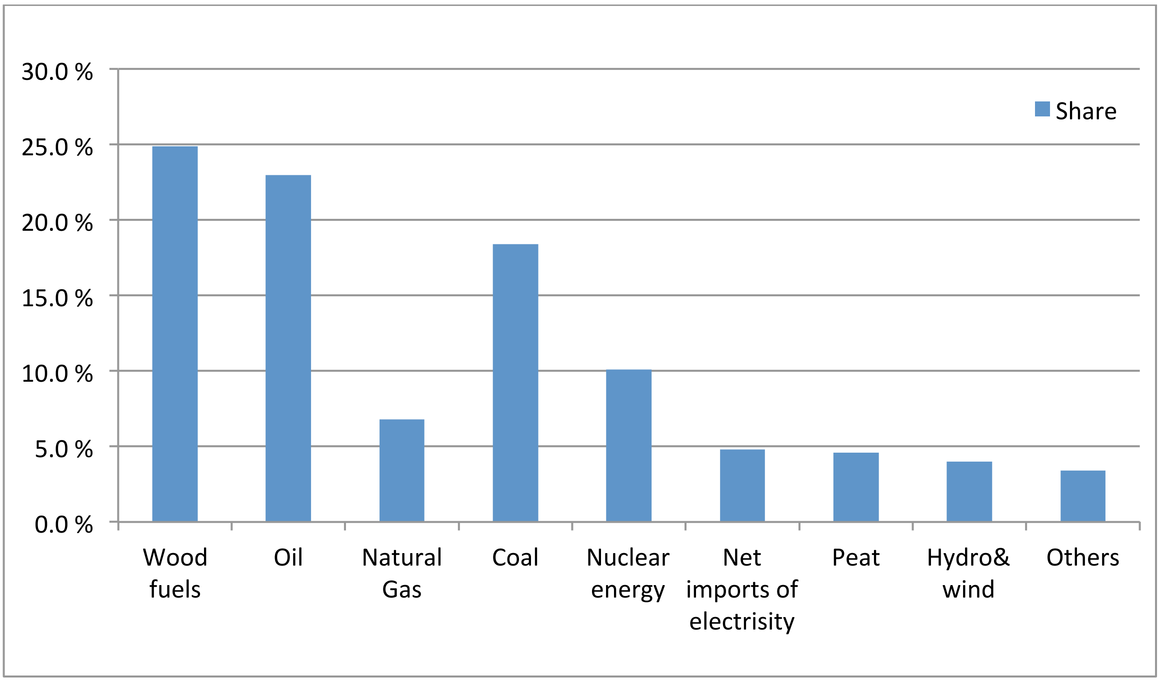

Figure 3. Share of different energy sources of total consumption in Finland, 2014 (Official Statistics of Finland (OSF), 2015)

However, the share of renewable energy slightly increased in 2014, compared to the previous year, amounting to approximately 32% (figure 4) of total primary energy consumption. Fossil fuels, although there is a 7% decrease compared to 2013, still make up for altogether 40% (oil 23%, natural gas 6.8% and coal 10.1%). (Official Statistics of Finland (OSF), 2015, p.11)

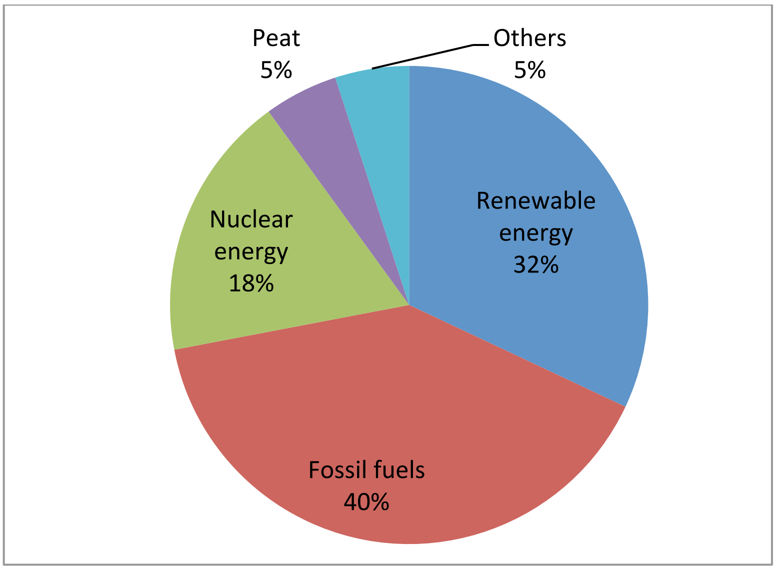

Figure 4. Share of renewable energy of total primary energy consumption in Finland, 2014 (Official Statistics of Finland (OSF), 2015)

According to Eurostat, the statistical office of the European Union, the total energy consumption of Finland in 2012 was 25.3 Mtoe, of which 43% was consumption by industry, 19% was by transport and 38% was by households, trade and service (Eurostat, 2014, pp.81-88). Compared to national statistics made by Finland for 2014, the industry sector share increased to 47%, the transport sector share declined to 16% and households and others remained stable through these two years (Official Statistics of Finland (OSF), 2015, p.11). Therefore, it can be concluded that industry has received relatively more development than transport.

2.1.2 Importance of Bioenergy

In order to tackle climate change, the EU Emissions Trading Systems (EU ETS), also known as "cap-and-trade", was introduced in 2005. The idea was to set a cap on the total amount of greenhouse gas (GHG) that industries can release each year and these emissions are monitored. A fixed number of allowances, representing the right to emit a specific amount of GHG, are given to companies under the trading system to cover their emissions. Companies that do not have enough credits can buy extra allowances from companies who can easily cut their emissions. It assures that the emissions are cut because of the cost for companies, otherwise they will face heavy fines if the emissions exceed the cap. Over time, the cap is reduced, fewer allowances are issued and the total emissions are reduced. EU ETS is an effective way that enables power stations, industrial plants as well as airlines to look for alternative solutions, which are environmentally friendly. At the same time, technologies to utilize renewable energy sources (RES) are developed. (The EU Emissions Trading System (EU ETS), 2015)

Other renewable energy forms, such as hydropower and wind energy, are very dependent on the availability of suitable locations. In contrast, bioenergy is readily obtainable since it is energy from organic matter that appear broadly. Furthermore, although wind and solar energy offer zero fuel cost, they only produce electricity when it is sunny or windy, which can cause higher capital costs and lower utilization rate than bioenergy (Biomass Versus Fossil Fuels, Solar and Wind, 2015).

The "Bio" part of the term "Bioenergy" refers to life and biomass that is biological material derived from living organisms, which are abundant (A. Jansen. 2013, p.113). The most common type of bioenergy is biofuels such as biodiesel and bioethanol. They are important because they are expected to replace petroleum fuels and natural gas in the future. Unlike petroleum fuels, biofuels have the potential to reduce greenhouse gas emission and a country's dependence on conventional fossil fuels. As people might know, fossil fuels were formed millions of years ago. When burning them, carbon dioxide as well as other GHGs are released, which were absorbed in ancient time. Making use of biofuels itself generates about the same amount of carbon dioxide as fossil fuels do.

But the positive side is that the carbon dioxide produced is absorbed by plants, which can be converted into biofuels again and create a carbon cycle.

2.2 Biomass as an Energy Source

Biomass refers to all kinds of organisms produced directly or indirectly by the photosynthesis process. Plants absorb solar energy to convert water and carbon dioxide from air to sugars, which will then be stored as chemical energy in the plants. Plants such as sugarbeet and sugarcane store the energy as simple sugars, while some plants store the energy as more complicated sugars, which are called starches. (A. Jansen. 2013, p.25).

As shortly mentioned in the last chapter, biomass is a type of renewable energy source and is considered as carbon-neutral. The reason is that biomass combustion, for instance, produces the same amount of carbon dioxide as biomass itself absorbs. In other words, carbon is cycled in the same loop (figure 5) rather than having the carbon dioxide level increased in the atmosphere.

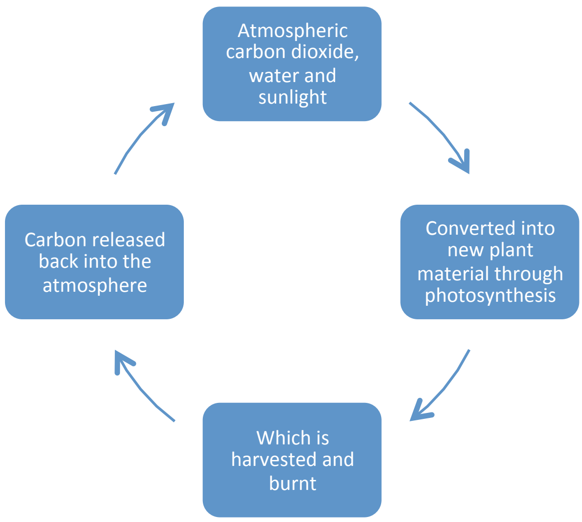

Figure 5. Biomass cycle (Closed Carbon Cycle, 2015)

The feedstock of biomass can be agricultural residues, forestry residues and energy crops. Organic waste such as municipal solid waste, animal waste and sewage sludge are considered to be biomass as well, because they started as plant matters.

2.2.1 Biomass Utilization

Mankind has already been burning wood to generate heat for thousands of years and this activity is referred to as conventional cooking, which is still done nowadays all over the world (A. Jansen.

2013, p.113). This kind of direct combustion, using wood as feedstock, is easy, cheap and popular, but has low efficiency. On the other hand, pellet heating (figure 6), a relatively new application that is popular in EU countries, has much higher efficiency and lower CO, NOx and dust emissions (Harvey, 2010, p.185). This is due to the use of biomass pellets as feedstock, which is a mixture of sawdust, wood shavings, bark, etc.

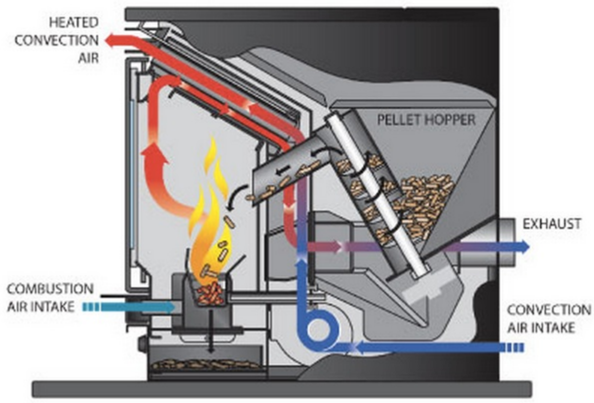

Figure 6. Pellet heating system (Introducing the Fireplace of the 21st Century, 2013)

Apart from direct combustion, solid biomass can also be burned at high temperatures in a gasifier with the addition of a limited amount of oxygen. Generated gases consist of CO, H_2, CH_4 and CO_2, which can be used for cooking, district heating or generating power directly. However, the formed gases are difficult to store and thus, increase the complexity to this kind of system. (Harvey, 2010, p.188)

To convert biomass to bioethanol, there are two key reactions involved. The first one is called hydrolysis, where complex polysaccharides in feedstock are converted into sugars with the help of acid and enzymes as catalysts. In a fermentation reaction, sugars act as food for yeast or bacteria and are then converted into ethanol. Another type of biofuel, biodiesel, can be produced from a process called transesterification. The idea is to convert triglyceride oils contained in vegetable oils, animal fats or recycled greases to biodiesel and glycerin by reacting with alcohol, such as methanol. Heat and a strong base catalyst, such as NaOH, are required in the process. (A. Jansen. 2013, p.26)

Anaerobic digestion, (AD), is a method to convert biodegradable materials into biogas, with the addition of bacteria in oxygen-absent surroundings. Biogas consists of approximately 60% of methane and 40% of carbon dioxide, which then can be used for heating or generating electricity. Since biogas is the starting point of this thesis, focus on AD is then enhanced. Thus, more detailed information about AD can be found in Chapter 2.3.

2.2.2 High Demand in Biomass

As the oil prices rise and the cost to produce biomass is falling, investing in biomass becomes very attractive. According to the International Energy Agency, biomass is the fourth energy source just after oil, coal and natural gas (Biomass: The fourth energy source, 2012). According to the scope of EU 2020, GHG emissions are expected to be reduced by 20%. Therefore, EU members are stimulated to expand their biomass plants in order to increase their capacity to produce renewable energy. In table 1, there is summarized information of biomass expansion plans for some of the Nordic countries.

Table 1. Biomass expansion plans for Nordic countries (A. Jansen. 2013, p.123)

Country	Capacity (MW) 2011	Expected Installed Biomass Capacity (MW) 2020
Sweden	2664	2872
Finland	1980	2920
Denmark	879	2404

According to an estimation made by the European Environment Agency (EEA) in 2006, EU requires 1.8 billion toe (tonnes oil equivalent) primary energy in 2020. Biomass is able to contribute 13%, which is 236 million toe (tonnes oil equivalent) of the total amount, keeping in mind only 69 million toe biomass was actually provided in the year 2003 (Biomass potential- Agriculture and rural development, 2015). Since the biomass potential of forestry and waste is relatively stable over time, the focus and the big uncertainty come with the question of how much food materials are needed to produce energy and whether EU agriculture is able to supply. This may raise food prices and cause great pressure. One can also say that agriculture is the key for larger biomass expansions. The need to find new biomass sources is also increased and materials, such as algae, have received attention.

2.3 Anaerobic Digestion

Organic substances can be naturally decomposed with the absence of oxygen or artificially decomposed in airtight digesters and this is called anaerobic digestion (AD). AD is a complex process, which consists of degradation of biomass (e.g. sewage sludge, food residues, crops, animal slurry, etc.), during which biogas containing methane (CH_4) is formed. Produced biogas can be used for multiple purposes: heating, generating electricity and as biofuel. Apart from biogas, another end product is a low odor, nutritious effluent that is suitable for land application, i.e. fertilizer.

Fundamentally, AD of organic matter is a combination of four different steps: hydrolysis, acidogenesis (also known as fermentation), acetogenesis and methanogensis. As the name suggests, it requires strict anaerobic conditions to take place. In other words, neither oxygen nor nitrogen may be found in the digester. The feedstock is pumped into a sealed digester, or fermenter, where different groups of bacteria present support the digestion by breaking down the matter into biogas and effluent. Some parameters, for instance temperature, pH, etc. are also significant, which is explained later in the text. Figure 7 shows a diagram that illustrates this process.

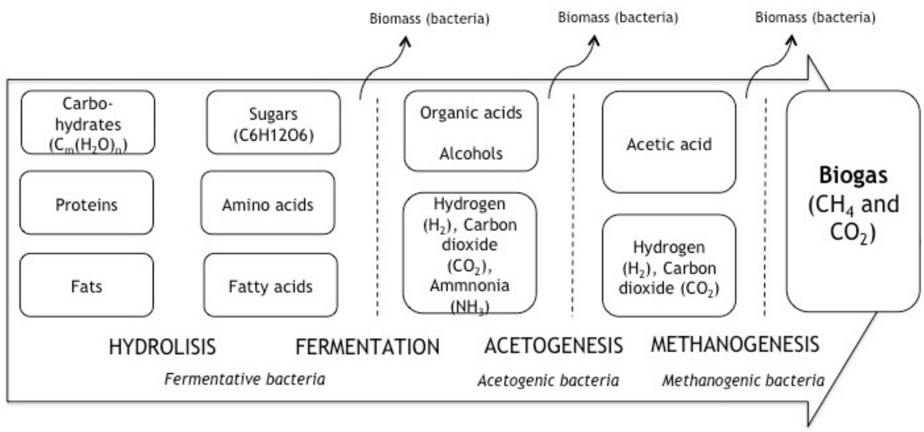

Figure 7. AD process (Spuhler, 2015)

In the hydrolysis step, the feedstock reacts with water, and complex compounds such as lipids, polysaccharides and proteins are broken down by enzymes into soluble organic substances, e.g. fatty acids and amino acids. Then, the components formed during hydrolysis further split during the second step acidogenesis. During this phase, volatile fatty acids as well as other by-products such as ammonia (NH_3) and CO_2 are generated. The most important component generated is acetate, because it can be directly used as a substrate by methanogenic bacteria. An acetate is not only produced in acidogenesis. It is also produced during acetogenesis. In this stage, low molecular weight volatile fatty acids are converted into acetate, CO_2 as well as H_2. Finally, CH_4 is produced in the methanogensis step by the help of methanogenic bacteria. (Nayono, S., 2010, p.9)

Each group of micro-organisms, during the digestion, has a different optimum pH range, but generally it varies between 6 and 8 (Igoni, A. et al., 2007, p.435). Nayono, S. (2010, p.11) states that acidogenic bacteria can function at pH 5. However, the methanogenic bacteria only function well in the pH range of 6.5-7.5, optimally between 6.8 and 7.6. When the pH is lower than 6.3 or higher than 7.8, the methane production in turn will decrease. The pH value in an anaerobic digester can be controlled by the bicarbonate buffer system and it should be slowly added to prevent causing adverse impacts on the bacteria (Seadi, T. et al., 2008, p.26).

The temperature plays an important role during the AD process, since it directly affects the physicochemical properties of the feedstock and the metabolism of micro-organisms (Appels, L. et al., 2008, p.759). Generally, there are three temperature ranges: psychrophilic (< 25 ºC), mesophilic (25-45 ºC) and thermophilic (45-70 ºC). The choice of temperature depends on the characteristics of feedstock, but modern designs are usually operated under mesophilic or thermophilic conditions (Seadi, T. et al., 2008, p.23). According to Nayono, S. (2010, p.12), AD with mesophilic conditions has the optimum temperature around 35 ºC and with thermophilic conditions around 55 ºC. Figure 8 shows the influence of temperature on the rate of the anaerobic digestion process. A high temperature has several benefits, such as increasing solubility of the organic compounds, enhancing biological and chemical reaction rates, etc. However, it could also increase the free ammonia content, which causes inhibition of the micro-organisms (Appels, L. et al., 2008, p.759). Thus, it is important to control the high temperatures in the AD process, since it has significant influence on biogas production.

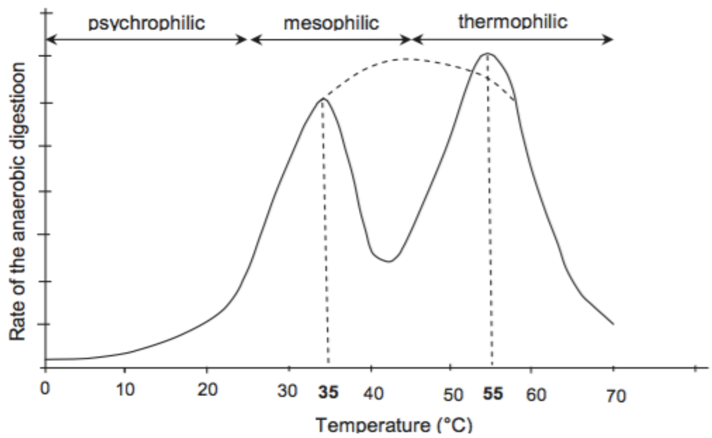

Figure 8. The influence of temperature on the AD rate (Nayono, S., 2010, p.12)

Volatile fatty acids (VFA), essentially, are intermediate products such as acetate, propionate, butyrate and lactate produced during acidogenesis. The accumulation of them can affect the stability of the AD process by reducing the pH value. Nonetheless, some substrates such as animal manure have high alkalinity, which means VFA must exceed a certain level to be detected due to the drop of pH. Then, the VFA concentration will be too high to be controlled as it was already inhibiting the AD process. (Seadi, T. et al., 2008, p.26)

The hydraulic retention time (HRT) describes the average time that a certain substrate is retained in the digester, since an AD is usually a continuous process. Nayono, S. (2010, pp.15-16) indicates that the HRT of an anaerobic digester treating solid wastes is between 3 to 55 days, depending on types of feedstock, operating temperature and configuration of the digester. As for solid waste from poultry slaughterhouses, the HRT is longer (50-100 days).

3 Biomethane

The main product of AD, biogas, is an environmentally friendly and a sustainable biofuel, meaning that it is obtained without causing harm to the surroundings. Generated biogas consists of CH_4, CO_2, as well as small fractions of O_2, H_2S, H_2O and other trace gases. The composition of biogas gained from AD can be seen in table 2.

Table 2. Typical biogas composition (Gerlach, F., Grieb, B., & Zerger, U. 2013)

Component	Chemical Symbol	Concentration by volume (%)
Methane	CH_4	50-75
Carbon Dioxide	CO_2	25-45
Water vapor	H_2O	2-7
Sulfide	H_2S	0.002-2
Nitrogen	N_2	< 2
Ammonia	NH_3	< 1
Hydrogen	H_2	< 1
Trace gases	/	< 2

3.1 Biomethane as Transport Fuel

Nowadays, biogas is mainly converted directly into electricity, or used as heat, in a cogeneration unit, to supply homes, schools and even industrial buildings. Another option, which is also the focus of this thesis, is to purify the gas, by eliminating the CO_2, and produce biomethane. The purified biomethane has the same properties as natural gas and can function as a highly efficient and environmentally friendly fuel for natural gas- or biogas cars, or be injected into the natural gas grid.

Biomethane as transport fuel is generally still a young industry in Europe, despite the fact that it has already been proved that the crude oil dependency can be broken. Around 82% of motorized road vehicles in Pakistan used methane as fuel in 2010 (Lampinen, 2013, p.5, p.29). For transport purpose, it is usually in the form of compressed biogas, (CBG), or liquefied biogas, (LBG). CBG is typically used for light transport such as cars, vans, urban buses, boats, etc., while LBG is the fuel for heavy transport, such as trucks, intercity coaches and ships, due to the fact that it has three times higher energy density than CBG (Lampinen, 2012, p.12).

A benefit of using biomethane as transport fuel other than environmental and energy security, is that it is suitable for all engine types and all transport modes. The upgraded biogas has around 40 more octane numbers than gasoline fuel (table 3), which can reduce the likelihood of the problem of engine knocking. Besides, all factories which manufacture biogas vehicles in Europe, install bifuel systems on their cars (Lampinen, 2015), meaning either biomethane or gasoline can be used as fuels.

Table 3. Octane number of different fuels (Lampinen, 2015)

Fuel	Octane Number
Upgraded biogas (biomethane)	130-150
Upgraded Natural Gas	120-130
Formula-1 Gasoline	102
Best Consumer Gasoline	99
Normal Consumer Gasoline	95-98

3.2 Biogas/Biomethane Utilization in Finland

Biogas energy production and development is generally continually expanding across the EU. According to EurObserv'ER, in the year 2013, 13.4 Mtoe of biogas was produced in EU, which represents a 10.2% growth from 2012, even though there have been declines in two major biogas producing countries, Germany and Italy. From this amount of biogas produced, 52.3 TWh of electricity was converted, which is equivalent to 4499 ktoe of final energy. (EurObserv'ER, 2014a)

Finland started to collect national biogas statistics in 1996 and this has resulted in a series of reports regarding Finnish biogas production and utilization since 1994.The statistics originally didn't cover biogas as vehicle fuel, but Finland decided to extend the scope to traffic biogas and started to include it from the 2011 publication (Lampinen, 2014). Until now, there are only three countries, Sweden, Finland and Germany that include consumption of biogas in the transport sector in their national statistics. Table 4 below shows a summarized data regarding biogas production and utilization in percentage share of the three European countries mentioned earlier.

Table 4. Biogas production and utilization in Germany, Sweden and Finland in % share in Europe, 2013. (EurObserv'ER, 2014a), (EurObserv'ER, 2014b)

Country	Primary Energy Production of Biogas (% share in Europe)	Gross Electricity Production from Biogas (% share in Europe)	Gross Heat Production from Biogas (% share in Europe)	Biogas Fuel (% share in Europe)
Germany	50.2%	55.4%	24.1%	26.8%*
Sweden	1.0%	0.02%	2.6%	72.9%*
Finland	0.4%	0.3%	0.02%	0.3%*
* lack of data from other EU countries				

By the end of 2013, there were in total 95 biogas production plants in Finland, of which 42 were landfill plants and the other 53 were reactor plants. These 95 plants produced altogether 770 GWh of biogas in 2013, of which 404.4 GWh of heat and 151.3 GWh of electricity were generated and 32.8 GWh of biomethane was upgraded for vehicle use (Lampinen, 2014). In figure 9 below, one can find different usages of biogas in percentage in Finland.

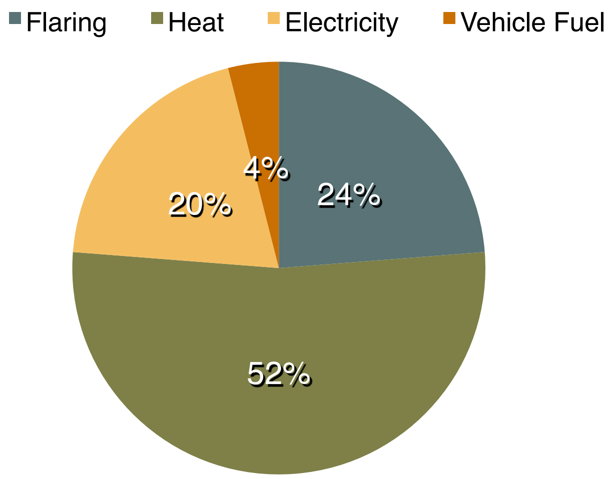

Figure 9. Biogas utilization in Finland (Lampinen, 2014)

According to Lampinen (2013, p.17), the data shows that Finland started to upgrade biomethane as vehicle fuel in the 1940s, but Junginger (2014, p.20) states that the first upgrading plant in the world was built in the 1980s. The reason could be that the lack of technology in the 1940s led to a slower development over the decades. However, the biomethane development was only boosted recently due to the taxation policy. From 1965, vehicles that used gasoline and diesel as fuel had the right to receive lower taxes than vehicles using natural gas and other alternative fuels. This orientation delayed the development of biomethane and it was not until 2004 that the tax on alternative fuels was lowered (Thran, 2012, p.55). Nowadays, the Finnish government proposes the use of biomethane in the transport sector and many plants and filling stations are currently being planned and are under construction.

In 2014 there were 24 public biogas filling stations in Finland selling CBG100, which stands for 100% compressed methane fuel. The price was between 1.205 and 1.505 euro/kg, which is equivalent to 0.8-1.0 euro/liter gasoline. In total, there was an estimated number of 1800 compressed methane gas (CMG) vehicles in Finland. Most of them were cars and vans and around 100 CMG vehicles were trucks. (Lampinen, 2014)

3.3 Biomethane vs. Other Transport Fuels

Due to the fossil fuel shortage and environmental degradation, there has been a lot of attention transferred from conventional gasoline and diesel to crude oil independent alternatives. Among them, electric cars have received most attention from both media and politics. But only a small share of electric cars is finally in use, since there are limitations in electricity storage and charging. Hydrogen economy is also awaited, but there are practical, technological and economic issues that limit the development (Lampinen, A., 2013, p.5). Biomethane, as a potential alternative, received less attention, although it is mature enough to reinforce the fuel chain and it already possesses a large share of worldwide energy consumption (Lampinen, A., 2012, p.12). In this chapter, biomethane as vehicle fuel is compared with not only conventional fossil fuels, but also with other biofuels for the purpose of underlining its importance for sustainability reasons.

First of all, apart from gasoline and diesel as conventional transport fuels, there are five categories of alternative fuels classified in line with the report "Future Transport Fuels" published by European Expert Group (2011, p.38):

- Electricity and hydrogen/fuel cell
- Liquid biofuels: bioethanol, biodiesel
- Methane: natural gas (CNG, LNG), biomethane (CBG, LBG)
- Synthetic fuels: BtL, GtL, CtL and HVO
- LPG: butane and propane

As previously mentioned, biomethane is suitable for all the transport modes: from light road transport to marine and even airway. Table 5 below covers all the different alternative fuels and their performance in different transport modes in terms of short/medium/long travel distance. It can be seen that only liquid biofuels, synthetic fuels and methane based fuels are suitable for all kinds of modes of transport. For now, Airbus and Boeing are developing LNG airplanes (Lampinen, A., 2012, p.14). Therefore, regarding performance of transport suitability, there is no doubt that biomethane should be viewed as an important alternative fuel.

Table 5. Suitability of different fuels under different transport modes (Lampinen, A. 2012, p.14)

		Road/passengers			**Road/freight**			**Rail**	**Water**			**Air**
		short	med	long	short	med	long		inland	short-sea shipping	maritime	
Electric	BEV											
	HFC											
Biofuels (liquid)												
Synthetic fuels												
Methane	CNG CBG											
	LNG LBG											
LPG												
(Shadowed grids mean there is such appearance).												

Table 6 shows the typical lower heating values (LHV) of selected vehicle fuels and their CO_2 emissions, as a comparison with gasoline. Biomethane and natural gas have the highest energy content of 13.89 kWh/kg, which is attractive for vehicle applications. Furthermore, the CO_2 emission is the least when burning one kWh of biomethane/NG compared to burning one kWh of gasoline. In vehicles with identical properties and engine efficiency, biomethane/NG could achieve a 29.2% CO_2 reduction if gasoline is used as a baseline of 0% CO_2 reduction.

Table 6. Energy content and CO_2 emissions of five different fuels (NGVA Europe, 2009)

Fuel type	LHV (kWh/kg)	CO_2 in g/kWh	Theoretical CO_2 reduction in %
Methane (NG/biomethane)	13.89	198.0	29.2
LPG (propane)	12.67	236.8	15.3
LPG (Butane)	12.58	241.2	13.7
Diesel	11.86	267.5	4.3
Gasoline	11.77	279.5	0.0

In addition to transport performance, energy content and CO_2 emissions, fuel prices are also comparable between different fuels. Table 7 shows the fuel price of four types of vehicle fuel in Finland in 2015. Among them, gasoline and diesel fuel prices were obtained from the current fuel market, and biomethane and natural gas fuel prices were obtained from the webpage of Gasum, who is an operator of biogas and natural gas filling stations. It can be seen that biomethane and natural gas have lower prices than conventional gasoline and diesel. Moreover, there is no excise duty on biomethane. (Gasum, 2014b)

Table 7. Fuel price of four types of fuel in Finland, 2015 (Gasum, 2014b)

Gasoline	Diesel	Biomethane	Natural gas
1.52 euro/l	1.34 euro/l	0.928 euro/l	0.851 euro/l

Based on the comparison, biomethane/natural gas has large energy contents, less CO_2 emissions, lower market prices and are suitable for all types of engine and transport modes. Overall, it is clear that they are suitable as transport fuels in every aspect, whereas biomethane offers larger environmental benefits than natural gas. Now it is only a political decision that can alter the energy source selected in the transport sector.

4 Biomethane from Biogas Upgrading

The utilization of biogas as transport fuel requires treatment. The energy content is in direct proportion to methane concentration and biomethane after upgrading has a higher energy content. Therefore, the large amount of carbon dioxide present in biogas should be removed in the upgrading process.

Before actually upgrading biogas to biomethane, water, hydrogen sulfide and other contaminants are generally removed and this is so-called gas cleaning. Some upgrading technologies are able to remove these impurities with CO_2 simultaneously, but others require removal of them beforehand. In this thesis work, the upgrading process mainly focuses on removing carbon dioxide out of biogas rather than other contaminants.

4.1 Upgrading Technologies

Several upgrading technologies are available nowadays at a pilot or plant level and some are still under development. In the subchapters below, one can find a review of state-of-art techniques in general. They are selected among many technologies because of their popular applications in Europe.

4.1.1 Membrane Separation

The principle of membrane separation is the result of the selective permeability (figure 10) of membranes due to different partial pressure between gases. This type of technique was first developed in the 1990s in the USA (Bauer, F., Hulteberg, C., Persson, T., & Tamm, D., 2013a, p. 28) and can generally be grouped into two systems: 1) gas-gas separation and 2) gas-liquid absorption separation.

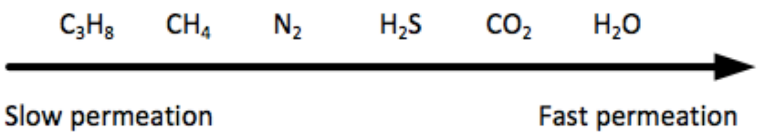

Figure 10. Permeability of different substances (Bauer, F., et al. 2013a, p. 29)

Gas-gas separation uses a high pressure membrane wall in the middle, which is typically a hollow fiber membrane, with gases being present on each side. The operating pressure is normally above 20 bars, but not exceeding 30 bars. However, there is a newer alternative to be operated under 10 bars, with less methane gas loss. The methane content after one treatment is maximum 92%. Thus, it is recycled in the process and generally after 2-3 treatments, 96% or more methane is achieved. After upgrading, the CO_2-rich offgas still contains around 10% of CH_4, which is then flared and used for heat production. (Ryckebosch, E., Drouillon, M., & Vervaeren, H., 2011, p.1641)

Another type of system, gas-liquid absorption separation, is operated under atmospheric pressure at 1 bar. A micro porous hydrophobic membrane separates the raw gas from the liquid absorbent. An absorbent, such as amine solutions, is present on one side and absorbs CO_2, which can diffuse through the membrane. Furthermore, the liquid absorbent is not able to flow into the gaseous side due to slight pressurization of gas. The upgraded methane content can achieve 97% after one step, and amine solutions after heating can generate pure CO_2 that can be sold for industrial applications (Ryckebosch, E. et al. 2011, p.1642). The interior look of a biomethane upgrading plant using membrane separation can be seen in figure 11.

Figure 11. Interior of a membrane biomethane upgrading plant (Makaruk, A. et al., 2010, p.84)

Table 8 summarizes the advantages and disadvantages of membrane technology. It is a compact system with less area use, thus, providing an easy construction. Its electricity consumption is relatively moderate and does not require heat. The cost of membrane separation is between 0.12-0.22 euros per Nm^3 of biogas (Elizabeth K., Warren H., 2010, p.21). However, it is estimated that the lifetime of a membrane is usually 5-10 years, which can raise the investment cost by 3-4% (Bauer, F. et al. 2013a, p.33). Meanwhile, compared to the chemical scrubber, membrane technology has a lower methane yield, which is also considered a negative point (Ryckebosch, E. et al. 2011, p.1640).

Table 8. Membrane separation pros & cons (Ryckebosch, E., et al. 2011, p. 1640)

Advantages	Disadvantages
Compact, easy to construct	High membrane cost
Low energy and maintenance requirements	Low CH_4 yield
Low cost	Difficulties with yield and purity raises operating cost

4.1.2 Pressure Swing Adsorption (PSA)

Pressure swing adsorption (PSA) was first introduced in the 1960s and it has been developed continuously for decades (Jyväskylän Yliopisto, 2010, p.13). Now it is one of the most popular techniques to purify gases.

As the name of the technique suggests, CO_2 present in biogas can be retained and released by highly porous materials under varied pressures due to the components' different molecular sizes. In other words, CO_2 has a molecular size of 3.4 Angstroms while the molecular size of CH_4 is 3.8 Angstroms. Thus, under high pressure of typically 8 bar (Ryckebosch, E. et al. 2011, p.1641), an adsorbent with a pore size of 3.7 Angstroms is able to let CO_2 enter and be retained. CH_4 cannot even enter into the matrix of the adsorbent and therefore, it passes through interstitial spaces and is separated (Jyväskylän Yliopisto, 2010, p.13). As for adsorbent materials, the most common ones are activated carbon and zeolite. Others could be silica gels and activated alumina, which also reflects the flexibility of PSA. After adsorption, CO_2 is desorbed from the adsorbent at low pressure and this is so-called regeneration (Grande, C., 2011, p.74).

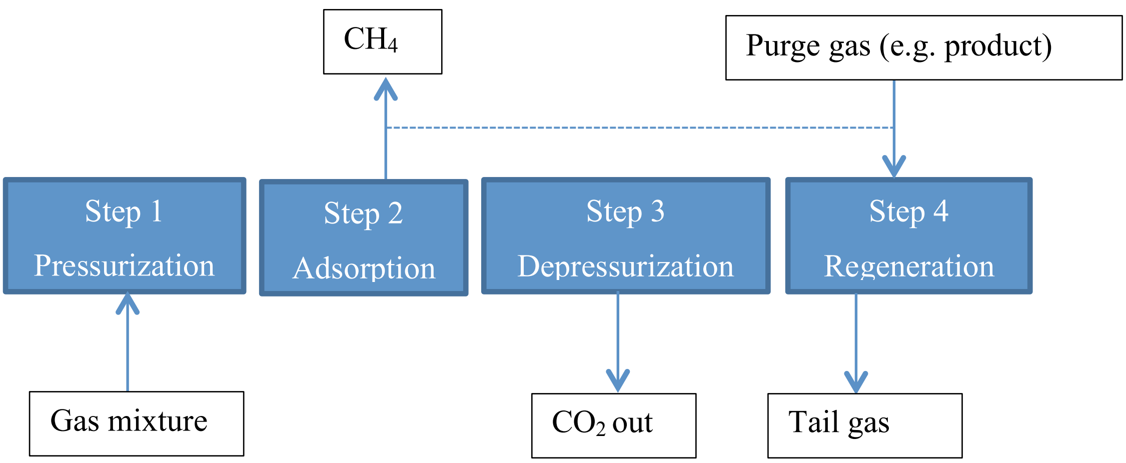

Figure 12. PSA Process Flow (Zakkour, P., & Cook, G. 2010, p.31)

With this technology, H_2S must be removed beforehand, since it can cause irreversible adsorption on adsorbent. Water must be removed as well, because it could destroy the structure of the material (Petersson, A., & Wellinger, A., 2009, p.9). Above in figure 12, one can find an example of a PSA process flow. There are usually four vessels working in parallel in the process: pressurization, adsorption, depressurization and regeneration (desorption). Finally, the methane content in the end product can reach 95-98% after upgrading (Ryckebosch, E. et al. 2011, p.1640). Figure 13 shows a typical PSA plant in Sweden.

Figure 13. PSA upgrading unit in Sweden. Left: The exterior; Right: The interior view (Bauer, F. et al., 2013a, p.25)

As mentioned earlier, adsorbent material can be very flexible. Another positive point is that the investment for such technology is low, especially for plants with small capacity (Bauer, F. et al., 2013b, p.506). On the other hand, it could also be a disadvantage that this technique is usually suitable for small-scale plants. In addition, a 4-step process also increases the complexity of the whole operation. These advantages and disadvantages are summarized in table 9 below.

Table 9. PSA pros & cons (Ryckebosch, E. et al. 2011, p. 1640)

Advantages	Disadvantages
Flexible material choice	Usually for small-scale plants
Relatively low capital cost	Complex system

4.1.3 Water Scrubber

The water scrubbing is the most popular upgrading technology in Europe, due to its easy and convenient operation. The idea is that since CO_2 is more soluble than CH_4 in water, biogas can then be upgraded by washing CO_2 out of it with water. In addition, H_2S can also be washed out, although it is usually removed prior to the real upgrading process along with other contaminants.

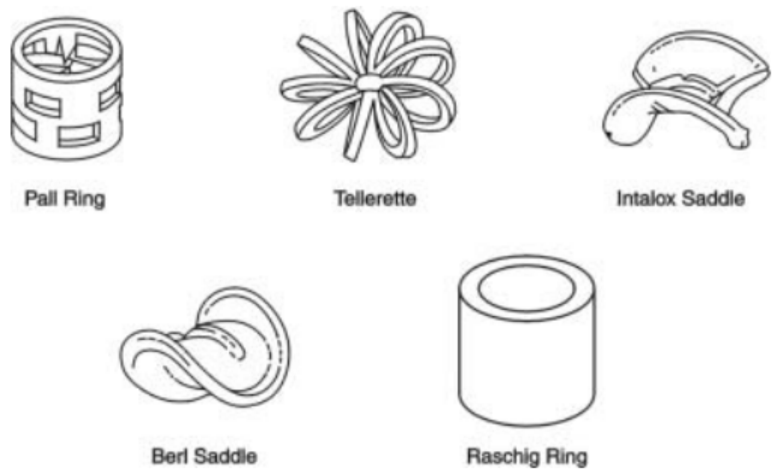

Figure 14. Designs of random packing material (The US Environmental Protection Agency, 1995, p.8)

The whole process is rather simple compared to other techniques. Cleaned biogas is pressurized at 9-12 bars in a compressor and then injected from the bottom of the scrubber unit. Water is flushed from the top of the tower in a counter flow. With random packing material settled in the column, water has a large contact area. In figure 14, one can see different designs of random packing. They are usually put in the scrubbing column and allow maximal mass transfer between water and biogas (The US Environmental Protection Agency, 1995, p.7). Then, CO_2 is absorbed by water and more concentrated methane gas rises and leaves from the top of the column. It is worth noticing that CO_2 is preferably absorbed at low temperatures (figure 15) (Petersson, A., & Wellinger, A., 2009, p.10). However, due to the slight solubility of CH_4, some of it can still be absorbed by water, which can be captured by depressurizing the water at around 2 bars within a flask tank. (Ryckebosch, E. et al., 2011, p.1639)

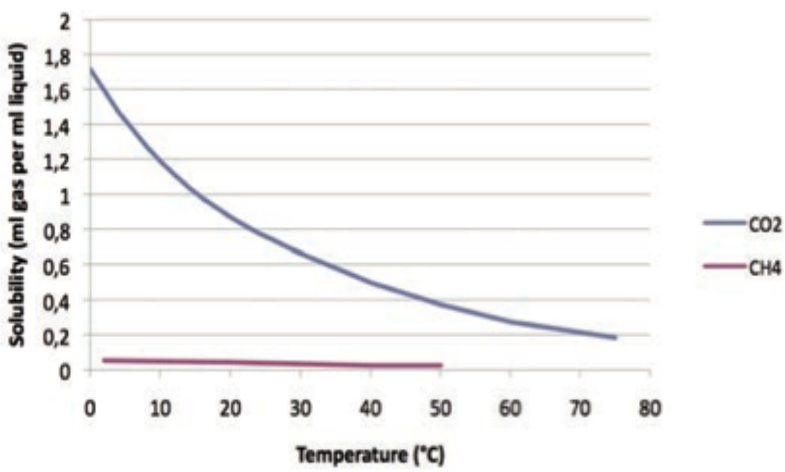

Figure 15. Solubility of CO_2 and CH_4 at different temperatures (Petersson, A., & Wellinger, A. 2009, p.10)

After upgrading, the produced biomethane is sent for drying and compressed to 200 bars for storage. A methane yield efficiency of above 97% can be achieved and no more than 2% of the methane can be lost (Ryckebosch, E. et al. 2011, p.1639). Moreover, water after absorption can be cleaned and regenerated by using a desorption unit, and CO_2 is emitted from the water. Figure 16 below shows a water scrubber upgrading plant in Nykarleby, Finland.

Figure 16. Water scrubber on Jeppo Biogas, Nykarleby, Finland (Jeppo Biogas, 2014)

In table 10, the advantages and disadvantages of the water scrubbing technology is summarized. Advantages include removal of both CO_2 and H_2S, easy operation and low CH_4 loss. Since water is the only liquid used, the process is relatively easy to control. However, it requires a large amount of water although some of it can be regenerated and wastewater should be properly disposed of. Bacteria growth could also cause clogging.

Table 10. Water scrubber pros & cons (Ryckebosch, E., et al. 2011, p. 1640)

Advantages	**Disadvantages**
No special chemicals are required	Requires a lot of water even after water regeneration
Both CO_2 and H_2S are removed	Clogging because of bacteria growth
Easy in operation	Disposal of wastewater
Low CH_4 losses (< 2%)	

4.1.4 Chemical Scrubber

The chemical scrubber works according to the same principle as the water scrubber. The major difference is that chemical solutions are used, not only to absorb, but also chemically react with CO_2 from biogas. This is most commonly performed using a solution of amines, with the reaction product being either in the molecular or ion form. The most used solvents are mono-ethanolamine (MEA), di-ethanolamine (DEA) or di-glycolamine (DEA), which can dissolve more CO_2 than water (Jakub, N., Jecha, D., & Stehlik, P., 2013, p.518). One can find a chemical scrubbing unit in figure 17 below.

Figure 17. An amine scrubber used for biogas upgrading in Sweden. Image from Purac Puregas. (Bauer, F. et al., 2013a, p.19)

The chemical scrubber has a methane efficiency of above 99.5%, which is higher than the water scrubber due to the fact that methane does not react with amine. Therefore, the loss of methane can be prevented. After treating CO_2, amine can be regenerated by heating, although part of it should be replaced with new, because of its evaporation (Masebinu, S., Aboyade, A., & Muzenda, E., 2014, p.91) and CO_2 can be recovered for further usage.

An advantage of chemical scrubbing is that H_2S can be completely removed, since it reacts with amine solutions as well. Thus, it provides a very high methane yield compared to other technologies. It can even be operated at a low pressure. Disadvantages include additional chemical use, heat requirement and corrosion. These advantages and disadvantages are summarized in table 11.

Table 11. Chemical Scrubber pros & cons (Ryckebosch, E. et al. 2011, p. 1640) (Jyväskylän Yliopisto, 2010)

Advantages	**Disadvantages**
Complete H_2S removal	Additional chemicals
Very high methane yield	Requires heat to regenerate chemicals
Can be operated at low pressure	Corrosion

4.1.5 Organic Physical Scrubber

The organic physical scrubber and the water scrubber are very alike. But instead of using water, it uses an organic solvent, for example polyethylene glycol (also trademarked as Selexol), to dissolve CO_2. The reason is that CO_2 has a solubility of 0.18 M/atm in Selexol, which is about five times higher than in water, which then gives a satisfactory result of around 97% methane efficiency. The used adsorbent can be regenerated through heating or depressurizing. (Bauer, F. et al, 2013a, p.46)

Compared to the water scrubber, an organic physical scrubber has smaller column diameters, due to the lower flow of the organic solvent (Bauer, F. et al, 2013a, p.48). Since polyethylene glycol absorbs more CO_2 than water does, the amount of the adsorbent required is low, resulting in a smaller facility, but with the same capacity as others (Petersson, A., & Wellinger, A., 2009, p.11). H_2S is usually removed prior to the upgrading to protect the components in the system and to fulfill requirements in air pollution control regulations. However, due to the complexity of operation, it has not been widely applied in Europe. According to a list of upgrading plants made by IEA Bioenergy, there were 22 plants among 282 plants in total in Europe using organic physical scrubber until mid-2014 (Plant Lists, 2014). Figure 18 shows an organic physical scrubbing plant in Sweden.

Figure 18. Organic physical scrubber with a capacity of 1100 Nm^3/h of raw bio- gas. Image from Haase Energietechnik. (Bauer, F. et al., 2013a, p.47)

Table 12 summarizes the advantages and disadvantages of using an organic physical scrubber to upgrade biogas. Firstly, it completely removes all organic S compounds present in biogas. Meanwhile, compared to water, less liquid is needed to dissolve carbon dioxide. Yet, additional chemicals also raise the cost of consumables that are demanded. Both heat and electricity demand also increase the difficulty of operation compared to other technologies.

Table 12. Organic physical scrubber pros & cons (Ryckebosch, E. et al. 2011, p. 1640)

Advantages	Disadvantages
Removal of organic S compounds	Additional chemicals
Dissolve more CO_2 than water	Difficult in operation

4.2 Comparison

In this section, the five technologies that are considered mature enough will be compared. In order to provide a reference material for industrial upgrading plants that are still under planning, different aspects such as technical parameters, economical elements, etc. are compared. Several sources are used and compared to assure a detailed review.

From the technical property point of view, there are two major consumables to consider: electricity and heat. Both Bauer, F. et al (2013a, p.51) and Petersson, A. & Wellinger, A. (2009, p.13) say that the electricity consumption for the mentioned five technologies and resulting data can be found in table 13. The electricity consumption for different technologies is quite similar. It generally varies from 0.2 to 0.3 kWh/Nm^3 raw biogas with the exception of the chemical scrubber, which has an electricity consumption of maximum 0.15 kWh/Nm^3 raw biogas (Petersson, A., & Wellinger, A., 2009, p.13). However, the exact power consumption depends on parameters such as working pressure, unit size and so on. According to Bauer, F. et al. (2013a, p.51), for example, for the water scrubber, the specific electricity consumption is 0.23 kWh/Nm^3 when the plant capacity spectrum is around 2000 Nm^3/h, but increases to 0.3 kWh/Nm^3, if the capacity is as low as 400 Nm^3/h. Furthermore, winter/summer conditions could also cause a significant difference in electricity consumption, since the large amount of water used in such technology should be cooled during the summer. Both sources agree that the chemical scrubber has the least power consumption, because it can be operated at ambient pressure (Bauer, F. et al., 2013a, p.51), (Petersson, A., & Wellinger, A., 2009, p.13). Yet, a project report made by Vienna University of Technology (2012, p.13) that is under the Intelligent Energy (Europe Program), believes the electricity consumption of all five technologies should be around 0.2 kWh/Nm^3 higher than the numbers summarized by previous sources. It is difficult to provide a valid comparison of different technologies, because of different circumstances in different countries, as well as different technical layouts.

In addition to electric energy, only the chemical scrubber has an external heat demand of 0.5-0.6 kWh/Nm^3 biogas, (Bauer, F. et al., 2013a, p.52), which is used to recover the chemicals and facilitate the carbon desorption. It is worth mentioning that the heat can usually be provided by power plants nearby. For example, Svensk Biogas i Linköping AB in Sweden uses a chemical scrubber to upgrade biogas. During a study trip there, they explained that the reason why they specifically choose this technique is that they can get hot water from an incineration plant, which is just a few hundred meters away (Påledal, S., 2015). As for the organic physical scrubber, it does not need external heat. Because all heat required in the process is waste heat generated from the compressor and the regenerative thermal oxidation (RTO) unit that oxidizes the methane slip from the exhaust air (Bauer, F. et al., 2013a, p.47).

Table 13. Comparison of technical properties of different technologies

<table>
<tr><th>Parameters</th><th>Water Scrubber</th><th>PSA</th><th>Membrane Separation</th><th>Chemical Scrubber</th><th>Organic Physical Scrubber</th><th>Source</th></tr>
<tr><td rowspan="2">Electricity Consumption (kWh/Nm³ biogas)</td><td>0.23-0.3</td><td>0.2-0.3</td><td>0.2-0.3</td><td>0.12-0.14</td><td>0.2-0.28</td><td>(Bauer, F. et al., 2013a, p.51)</td></tr>
<tr><td>< 0.25</td><td>0.25</td><td>N.A.</td><td>< 0.15</td><td>0.24-0.33</td><td>(Petersson, A., & Wellinger, A., 2009, p.13)</td></tr>
<tr><td>Heat Consumption (kWh/Nm³ biogas)</td><td>None</td><td>None</td><td>None</td><td>0.5-0.6</td><td>Internal</td><td>(Bauer, F. et al., 2013a, p.51), (Junginger, M., & Baxter, D. 2014. p.19)</td></tr>
<tr><td>Working pressure (bar)</td><td>4-7</td><td>4-7</td><td>N.A.</td><td>No pressure</td><td>4-7</td><td>(Petersson, A., & Wellinger, A., 2009, p.13)</td></tr>
<tr><td colspan="7">N.A. Not Available</td></tr>
</table>

Gas purity is a measurement of the different technologies' ability to separate CH_4 from the raw biogas. Both Junginger, M., & Baxter, D. (2014. p.19) and Ryckebosch et al. (2011, p.1640) have this information in their research, and they both agree that the chemical scrubber has the best performance of 99.8% CH_4 purity in the standard configuration (table 14). The other four technologies have a relatively lower CH_4 purity, but they are still efficient enough to be applied.

For the water scrubber, H_2S can generally be removed together with CO_2, while others require an external cleaning process prior to upgrading. The chemical scrubber offers complete H_2S removal during the process, but an external H_2S removal device is recommended. On the other hand, a PSA and a membrane can separate H_2O in the procedure and the others need to remove H_2O beforehand. (Junginger, M., & Baxter, D. 2014. p.19)

Table 14. Comparison of technical performance of different technologies

Parameters	Water Scrubber	PSA	Membrane Separation	Chemical Scrubber	Organic Physical Scrubber	Source
CH_4 Content (%)	96-98	96-98	96-98	96-99	96-98	(Junginger, M., & Baxter, D., 2014, p.19)
	> 97	95-98	>96	>99	>97	(Ryckebosch et al., 2011, p.1640)
H_2S removal	Yes	External	External	External/ Yes	External	(Junginger, M., & Baxter, D. 2014. p.19)
H_2O removal	External	Yes	Yes	External	External	(Junginger, M., & Baxter, D. 2014. p.19)

From an environmental aspect, methane slip is considered within this category. Larger manufacturers can usually guarantee a 0.5-2% methane slip for most types of technologies, and 0.1% for chemical scrubbers (Junginger, M., & Baxter, D. 2014. p.20). However, sometimes the value rises due to temporary technical problems or different technical layouts. In table 15, three types of data sources regarding methane loss are listed. Generally, the PSA and the membrane technology have a relatively high methane loss. Emission treatment is required in some countries to lower the methane loss, for instance in Germany 0.2% of the methane emissions are allowed according to the law. In contrast, larger methane is allowed to be released in Sweden so that the off-gas treatment is not needed. (Junginger, M., & Baxter, D. 2014. p.20)

Table 15. Comparison of impact on the environment of different technologies

Parameters	Water Scrubber	PSA	Membrane Separation	Chemical Scrubber	Organic Physical Scrubber	Source
CH_4 loss (%)	2	2	0.5-20	0.04	4	(Vienna University of technology, 2012, p.13)
	< 2	< 10	N.A.	< 0.1	2-4	(Petersson, A., & Wellinger, A., 2009, p.13)
	1	3.5	13.5	0.1	4	(Starr, K. et al., 2012, p.995)
N.A. Not Available						

Economy is one of the main driving factors that are crucial for a company's survival, since companies consider whether they could make profits or not. In this part, investment cost, annual maintenance cost and price per Nm^3 biomethane are included. The specific investment cost for different upgrading technologies is significantly dependent on the capacity of the plant. According to Bauer, F. et al. (2013b, p.506), for a smaller capacity biogas plant with raw biogas less than 1000 Nm^3/h, a chemical scrubber has a slightly higher investment cost than other technologies (figure 19). Membrane separation has the lowest investment cost in the low to mid-scale range. And finally, for larger capacity biogas plants with more than 1500 Nm^3/h raw biogas, the investment cost for all the five technologies are about at the same level. Nevertheless, the figure presented should be understood as an indication for a plant that is in its basic form. The investment cost increases if there are supplementary equipment and specific requirements. Based on the investment indication, Junginger, M., & Baxter, D. (2014. p.19) also summarize the annual maintenance cost for different technologies: 3-4% of the investment cost annually for membrane separation due to the maintenance and replacement of the membrane and 2-3% for other technologies (table 16).

Table 16. Comparison of economic factors of different technologies

Parameters	Water Scrubber	PSA	Membrane Separation	Chemical Scrubber	Organic Physical Scrubber	Source
Annual maintenance cost (% of investment)	2-3	2-3	3-4	2-3	2-3	(Junginger, M., & Baxter, D. 2014. p.19)
€/Nm^3 biomethane	0.13	0.25	0.12_a-0.22_b	0.17_a-0.28_b	N.A.	(Korres, N. et al., 2013, p.175)
$_a$ Costs without H_2S removal $_b$ Costs with H_2S removal N.A. Not Available						

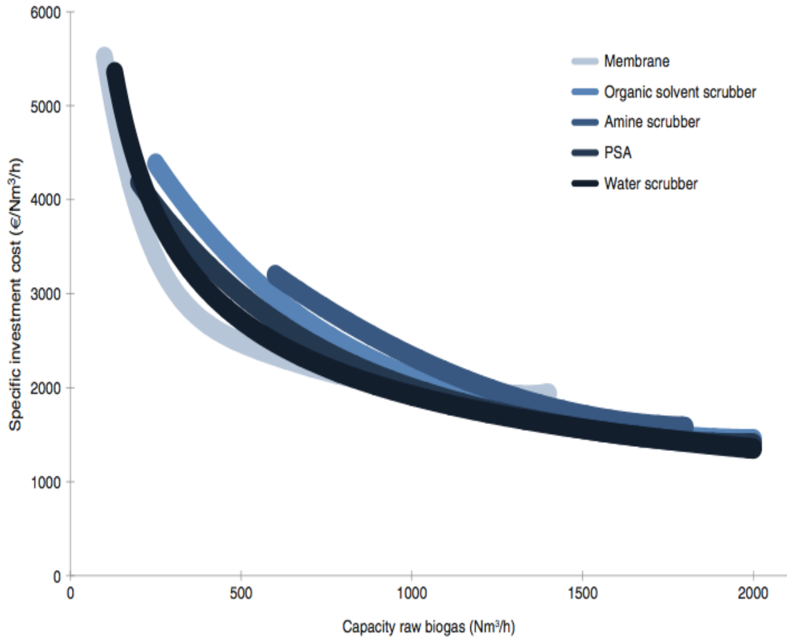

Figure 19. Comparison of investment costs for different upgrading technologies based on different plant capacity (Bauer, F. et al., 2013b, p.506)

Another important economic factor when evaluating the economic performance of upgrading technologies is the price per Nm^3 biomethane using Eq. 1, in which the interest rate on the investment cost is also considered. (Korres, N., O'Kiely, P., Benzie, J., & Routledge, J., 2013, p.174)

$$price\ per\ Nm^3 = \frac{\frac{investment}{depreciation\ period} + investment \times interest\ rate + annual\ cost}{Nm^3\ produced\ biomethane\ per\ year} \qquad \text{(Eq.1)}$$

According to Korres, N. et al. (2013, p.174), there was a study period of the cost of upgrading technologies in 2007-2009 and it is estimated that the high-pressure water scrubber had the least costs (including investment, maintenance and price per Nm^3 biomethane), while PSA had quite high costs. Meanwhile, the costs for membrane separation without H_2S removal were €0.12 and €0.22/Nm^3 of biomethane with H_2S removal (table 16). Similarly, the chemical scrubber had €0.17 and €0.28/Nm^3 of biomethane with and without H_2S removal.

Apart from economic parameters, the market share of different upgrading technologies (table 17) was collected by IEA Bioenergy Task 37 in 2012 (Junginger, M., & Baxter, D. 2014. p.20), with water scrubber as the most popular technology in the world, followed by chemical scrubber (22%) and PSA (21%). Membrane separation is a relatively new technology and occupied 10% of the market share. The organic physical scrubber had the least, with only a 6% share of the industry.

Table 17. Market share of different technologies in 2012

Parameters	Water Scrubber	PSA	Membrane Separation	Chemical Scrubber	Organic Physical Scrubber	Source
Market share (%)	41	21	10	22	6	(Junginger, M., & Baxter, D. 2014. p.20)

Once again, it is crucial to keep in mind that each upgrading technology has advantages and disadvantages. It is not possible to decide the best technology without knowing a company's specific parameters and expectations. The choice can be made based on economic factors or the highest achievable methane content, or even based on the presence/absence of suppliers of the technology in the particular country. For instance, due to the presence of water scrubber suppliers in Sweden and PSA suppliers in Germany, water scrubber is the most used technique in Sweden and PSA is the most popular in Germany. Plants in the Netherlands would prefer to use PSA, water scrubbers as well as membrane technology (Ryckebosch et al., 2011, p.1644). Moreover, there are also gains and losses that a company should evaluate and balance. For example, one can expect to lower the methane loss but energy consumption would increase at the same time. Therefore, it is strongly recommended that a company should perform an analysis of their needs, technical design and acceptable costs in order to find the most suitable technology.

5 Upgrading Plants in Finland

Before discussing the upgrading plants in Finland, it is worth mentioning that Finland has no natural gas reserves. Apart from biomethane produced, all of the natural gas used in Finland is imported from Russia. As for now, there are nine domestic commercial upgrading plants in Finland (figure 22) and their locations are as follows:

- Espoo
- Forssa
- Haapajärvi
- Jousta
- Kouvola
- Lahti
- Laukaa
- Nykarleby

Kalmari farm in Laukaa (figure 20) was the first commercial plant, starting operation in 2002. It is an outstanding example of a small-scale upgrading plant, that is not only self-efficient in heat, electricity and vehicle fuel, but it is also able to sell excess biomethane as transport fuel. The farm uses animal slurry as well as confectionary by-products as feedstock for biogas production. The raw biogas produced contains approximately 62-64% CH_4 and 36-38% CO_2. Some of the biogas is upgraded to more than 95% of the methane content using water scrubbers. The biomethane output for transport fuel is approximately 1000 MWh per year. Nowadays, there are around 50 local vehicles using biomethane from the filling stations nearby the farm and more than 100 customers have a biomethane refueling card (IEA Bioenergy Task 37, 2012). Kalmari farm even developed a second plant in Laukaa in 2014, which is in the same farm and the capacity is doubled to 2 GWh (Aittamaa, T., 2014).

Figure 20. Left: biomethane filling station on Kalmari farm. Right: bi-fuel tractor in test use on Kalmari farm (IEA Bioenerby Task 37, 2012)

Jeppo Biogas Ab in Nykarleby started its operation in 2014, with the main substrates coming from four pig slurry farms and potato waste from Jeppo Potatis. About half of the biogas is sent to the local industries, the other half is upgraded using a water scrubber and then transported to a food industry or to the Jepua gas filling stations. The upgraded gas has a methane content of nearly 99% and the estimated sales of biomethane as traffic fuel could reach 1-5 GWh. (Aittamaa, T., 2014)

Another operator of biogas plants in Finland, Gasum (figure 21), upgrades biogas to biomethane at three locations, Espoo, Lahti and Kouvola. The upgrading plant in Lahti started its operation in 2014, with a capacity of 50 GWh per year, which can supply 140 buses and 4500 cars annually. The plant in Espoo is in partnership with Helsinki Region Environmental Services. It has a capacity of 24 GWh per year, which can supply 64 buses and 2070 cars. Lastly, Kouvola has a capacity of 10 GWh per year - enough to fuel 28 buses and 900 cars. (Gasum, 2014a)

Figure 21. Gasum filling station (Gasum, 2014a)

Envor Biotech in Forssa is a new manufacturer and upgrading plant operator in Finland, who started to upgrade biomethane in 2013. Unlike other plants, it is for now the only plant in Finland using membrane separation. The current capacity of the plant can reach 1GWh (Aittamaa, T., 2014). Envor Biotech Oy mainly sells biomethane as vehicle fuel, but they are continuously researching future possibilities, for example pumping biomethane into the natural gas network is also under consideration. (Envor Biotech Oy, 2014)

Apart from the nine plants that already exist, there are several plants being planning. For example in Vaasa, where Novia UAS is located, a regional waste management company called Stormossen is planning to start upgrading biomethane in 2016. By then, the energy content is expected to reach 16 GWh, which can supply all twelve gas-buses in Vaasa and additionally 1000 cars (or 35 buses) for the public. However, the company cannot confirm the specific technique chosen until a contract is agreed on with a supplier (Saarela, J, 2015). In figure 22, one can see a map of biomethane upgrading plants.

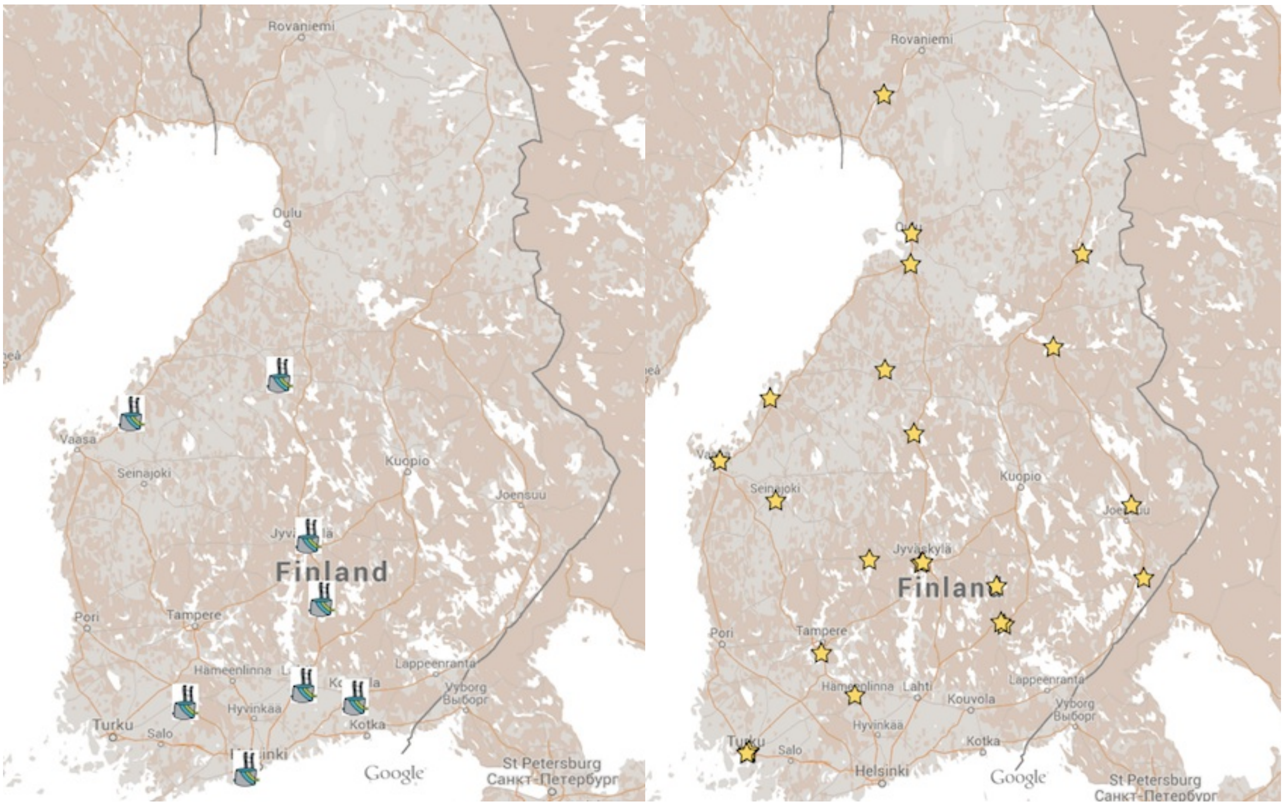

Figure 22. Left: upgrading plants' locations in Finland; Right: upgrading plants under planning in Finland (CBG100 Suomi, 2014)

Six upgrading plants in Finland, Laukaa-1, Laukaa-2, Haapajärvi, Forssa, Jousta and Nykarleby transport their upgraded biomethane to filling stations through local biogas pipelines. Nykarleby also transports CBG containers by using trucks. The other three plants, Espoo, Kouvola and Lahti, transport biomethane together with natural gas from Russia through national gas pipelines, (Lampinen, A. 2014). A map of CBG100 filling stations can be found in figure 23. In addition, there are three manufacturers of upgrading technologies in Finland, of which two of them, Metener and MetaEnergia, manufacture water scrubbers. Envor Biotech manufactures membrane separators and operates a biogas plant at the same time.

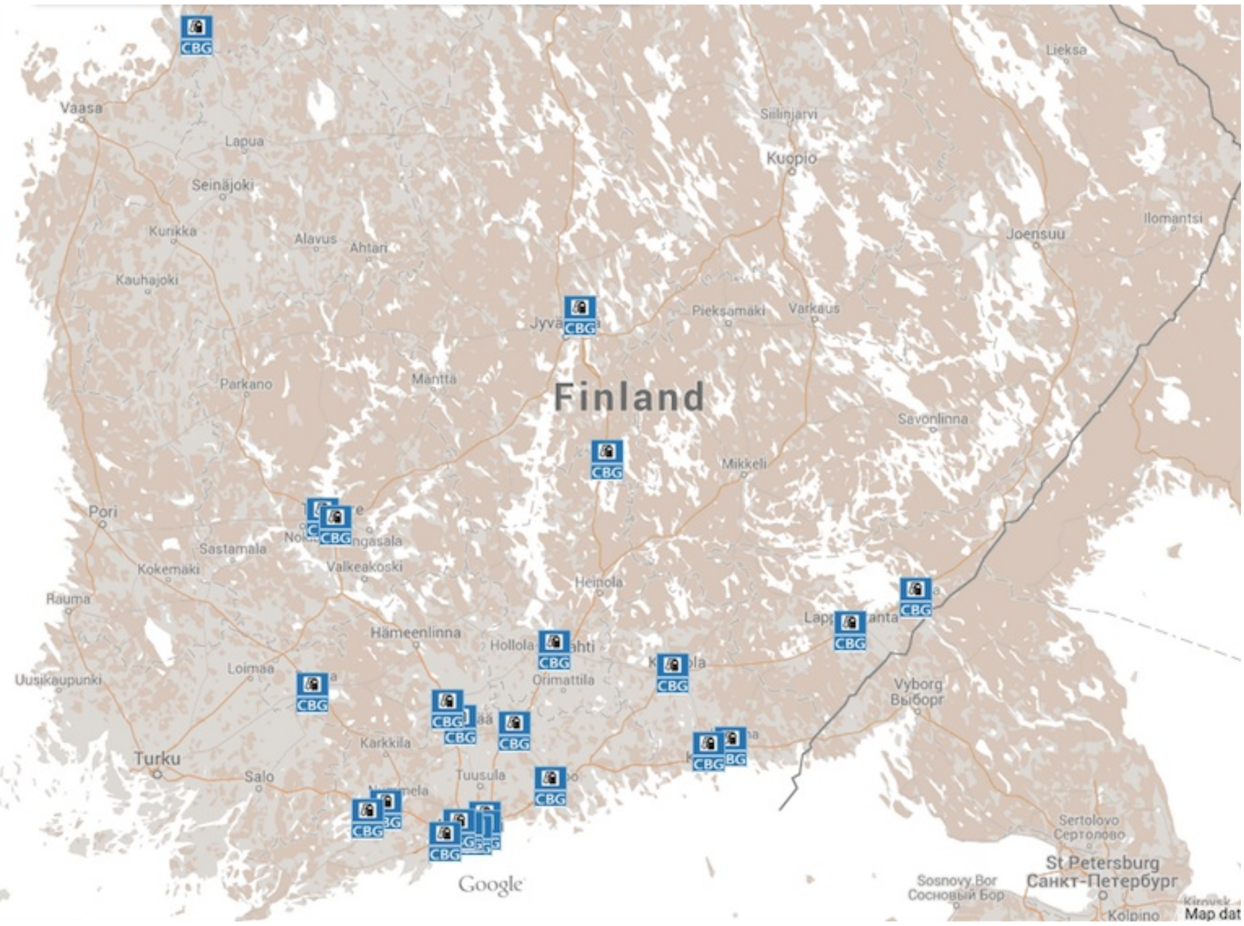

Figure 23. CBG100 filling stations in Finland (CBG100 Suomi, 2014)

6 Sustainability

The term sustainability has become more and more popular, as it is the key factor that affects decisions on new innovations and ways of thinking. The concept is defined by the UN World Commission on Environment and Development (Kuhlman, T., & Farrington, J., 2010, p.3438) as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". Thus, social, economic and environmental concerns of the biomethane development are important, a sustainability assessment is essential.

The EU has established the Renewable Energy Directive (Directive 2009/28/EC), in which Articles 17, 18 and 19 indicate sustainability criteria for biofuels and bioliquids with the purpose of promoting biomethane production in a sustainable form. The key principles are summarized as follows:

- The raw material used in biomethane production should not be obtained from land with high biodiversity value, land with high carbon stock (wetlands, etc.), primary forests and other woodland of native species;
- Biomethane shall contribute to climate change mitigation with significant GHG emission reduction compared to fossil fuels;
- Biofuels such as biomethane should be promoted in a way to encourage greater agricultural productivity and the use of degraded land. (Junginger, M., & Baxter, D., 2014, p.37), (The European Parliament and the Council, 2009)

In this thesis work, a fundamental sustainability assessment is made, in which three different aspects of environmental, social and economic issues are discussed. To be clear, no specific technology and location are determined. In contrast, upgrading biogas to biomethane as a whole is assessed.

6.1 Environmental Aspect

The upgrading of biogas into biomethane has a large environmental benefit. Biogas is mainly produced by anaerobic digestion, which is considered a treatment method of waste. Many European countries are facing overproduction of biowaste. Instead of using high-value agricultural crops, one could transform waste material into a valuable source. Moreover, the carbon in biogas is taken up from the atmosphere and through the photosynthetic process of the plants, which means that a closed carbon cycle is formed, without generating more GHG emissions to the planet. This factor fulfills Article 19 in the EU Directive 2009/28/EC as it has a positive impact on the climate change mitigation (The European Parliament and the Council, 2009, p.40). From the EU, as well as the national 2020 target point of view, it will also contribute to the renewable energy share in the transport sector.

Biomethane upgrading requires a certain amount of energy consumption, but as illustrated in Chapter 4.2, most technologies do not require heat consumption. Biomethane itself is also an energy source and consequently, the impact of energy use is not considered to be significant. Furthermore, most manufacturers of upgrading units can guarantee an efficiency of more than 95%, which could support the biomethane supply as transport fuel.

6.2 Social Aspect

Upgrading of biomethane from biogas requires a work force for production and transport of biomethane containers, and manufacturing of technical equipment, construction, operation as well as maintenance of an upgrading plant. Also, the construction of filling stations would help the rural development and bring business opportunities. In that case, new enterprises could be established and more jobs could be created.

Farmers, as the feedstock suppliers, could also benefit from the biomethane economy. For example, like Kamari farm, a combination of feedstock production, biogas plant and upgrading plant operation is economically attractive for farmers. On one hand, they have a way to treat their waste and get heat, electricity and fertilizer out of it and, on the other hand, they obtain fuel for their on-farm tractor applications or even selling for extra income.

6.3 Economic Aspect

The costs of building an upgrading plant is high, but the large input would lead to huge benefits in the future, especially after the biomethane network is well established and the filling stations are built. More importantly, the fact is that fossil fuels are limited resources and most European countries are strongly dependent on fossil fuels. Therefore, the development of a biomethane economy would help to reduce dependency on imported fossil fuels from Russia and the Middle East. Consequently, the security of the national energy supply would be increased and a circular economy would be created.

7 Biomethane Potential in Finland

Compared to biomethane, ethanol and biodiesel usually receive more attention from the public and policies. However, both environmental and resource considerations would significantly support biomethane as transport fuel. In this chapter, both EU strategies and targets in Finland are described.

7.1 EU Strategies

As a reminder, the EU 2020 goal is to have RES possessing a 20% share of the gross final energy consumption and with a 10% share in the transport sector. Overall, according to the current trend, the RES share in the final energy consumption is estimated to reach 20.9% by 2020 (European Commission, 2014, p.31). On 23 October 2014, EU leaders agreed on the 2030 policy framework for climate and energy, setting a target of at least a 40% GHGs reduction compared to 1990. In addition to 2030, the European Commission has adopted a roadmap 2050 for a low-carbon future. The vision is to virtually cut 80-95% or all the GHG emissions by the middle of the century (European Commission, 2013, p.3). Figure 24 shows a pathway to reduce 80% of emissions by 2050. For the transport sector specifically, there was a white paper issued in 2011, stating that no conventionally fuelled cars will be used in cities by 2050. Furthermore, 60% of GHGs will be cut in the transport sector (European Commission, 2011a, p.3). The primary mission, according to the European Commission (2011b, p.7), is to accelerate the development of electrification. Sustainable biofuels could be used as complementary fuel and especially developed for aviation and heavy duty trucks. However, if electrification could not be developed on such a large scale as expected, biofuels are awaited to achieve the same level of CO_2 reduction.

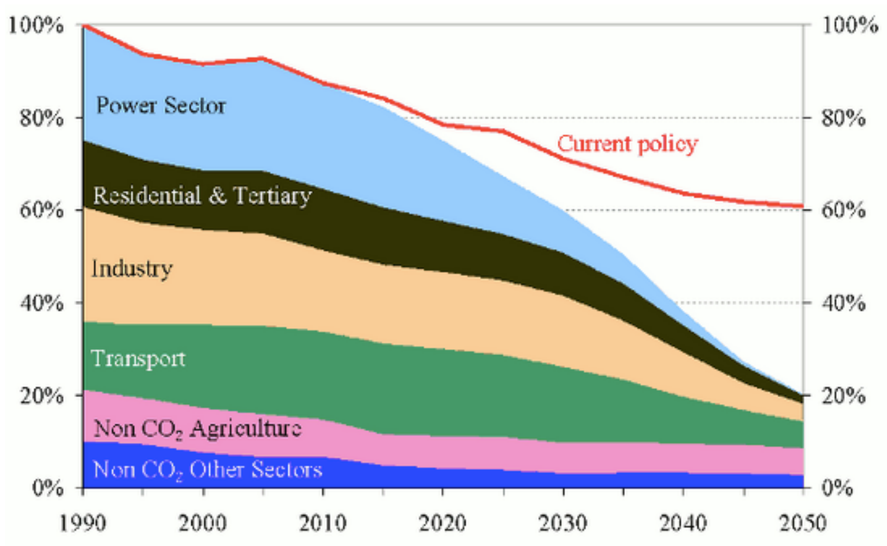

Figure 24. GHG emission reduction scheme by sector (European Commission, 2011b, p.5)

In order to achieve the EU 2030 and 2050 targets, the European Road and Research Advisory Council (ERTAC) (2014, p.95) has broken down the targets with every ten years as a milestone. Currently the first generation biofuels (biodiesel, biogas, syngas, bioalcohols, and vegetable oils) have established a relatively comprehensive market in Europe. A biomethane network is currently not well established in most European countries, because of the lack of customer friendly CNG filling stations. But biomethane as vehicle fuel generally has a great potential in the future, due to the existence of natural gas pipeline network. Countries like France and Spain are steadily developing their dense public NG refueling network. Thus, the year 2015 is considered a starting point of decarbonized road mobility. The first milestone would appear in 2025, when the natural gas filling station network is expected to expand strongly and new registered NG cars are increased to approximately 10%. By then, 20% of the used methane gas would be biomethane. For heavy duty vehicles, biomethane will play an important role, with an increase in market share of up to 30% in new registered NG buses and trucks. The second milestone will be in 2035 and a 50% CO_2 reduction is dominated by alternative vehicles. Meanwhile, methane refueling network is very well in place and the second generation biofuels are becoming industrialized. Then the final milestone, which is also the 2050 deadline, is to have methane refueling cover the whole of Europe. Finally, the goal to have a 60% carbon reduction in the transport sector is reached and a low-carbon economy is established. (ERTAC, 2014, p.96-98)

Despite the fact that much attention and preference is on electrification, the multiple advantages of biomethane are still attractive to the political agenda and markets. The GreenGasGrids project funded by the Intelligent Energy for Europe estimated that the level of biomethane could reach 18-20 million m^3 and contribute a minimum of 10% to GHG emission reductions of total gaseous vehicle fuel consumption if the necessary actions will be taken. The priority for each country is to extend the National Renewable Action Plans with a biomethane section specifically and decide on targets and measures to achieve them (Brijder, M., Dumont, M., & Blume, A., 2014, p.15). The latest news is that within the scope of Alternative Fuels Infrastructure Directive (Directive 2014/94/EU), countries should issue national plans for CNG filling station coverage by 2020 and LNG filling station coverage by 2025 and biomethane has the same targets as natural gas (The European Parliament and the Council, 2014).

7.2 Targets in Finland

Finland already took the target to reduce emissions into account in the development of a transport policy in 2011, stating, "*the use of biogas in vehicles will be promoted*" in its Government Program (Finnish Government Program, 2011, p.83). Lampinen, A. (2012, p.18) states that Finland has a methane vehicle target of a 2% share of registered road vehicles by 2020, which is set by using the historical model from Germany and Sweden as references. In other words, 4.6% of registered vehicles should use methane as transport fuel and it is about 60000 vehicles (figure 25). Currently, the development of methane in water transport is also optimistic, for instance there is already a new LNG passenger ship, Viking Grace, serving between Turku, Finland and Stockholm, Sweden. The target in 2020 is to have 20 methane-based ships, boats and ferries. Some mobile machines such as agricultural tractors and light vehicles are expected to use methane as fuel, but there is no such plan for air vehicles. In total, the methane consumption target for 2020 is 2.5 TWh, wherein the biomethane consumption would be 1 TWh (40%). As mentioned in Chapter 5, there are now nine upgrading plants in Finland producing biomethane. By 2020, the number is expected to increase to 30 and 100 biomethane filling stations will be built. (Lampinen, A., 2012, pp.18-19)

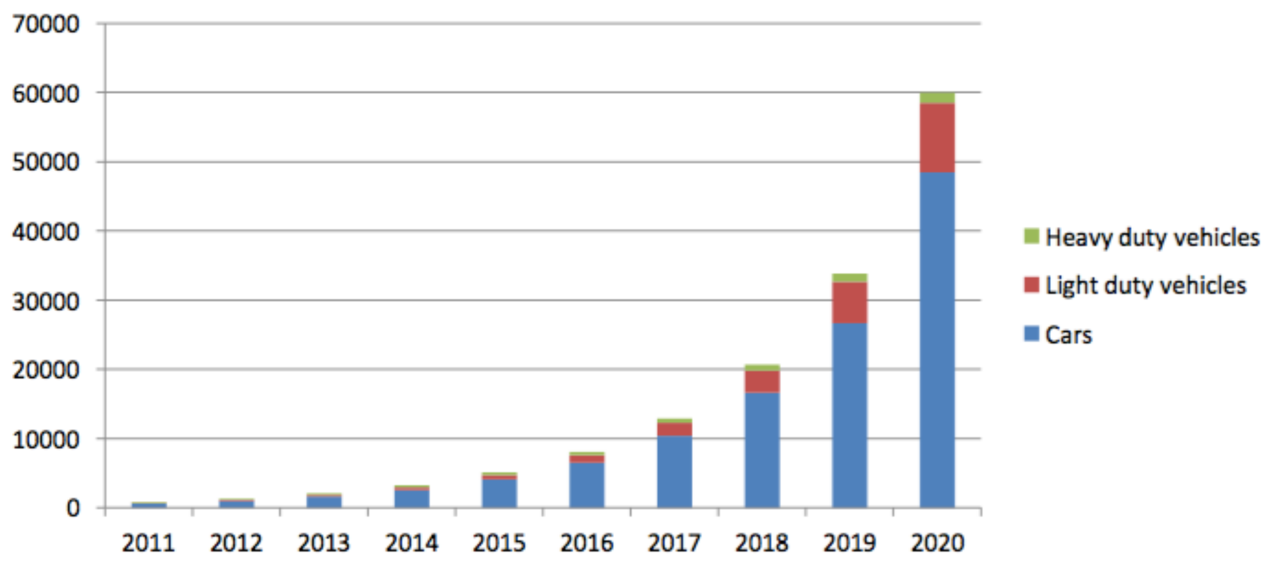

Figure 25. 2020 methane targets for road methane vehicle development, Finland (Lampinen, A., 2012, p.18)

As a response to the EU White Paper on Transport (COM(2011)144), Finland has set a goal to end the utilization of conventional gasoline, diesel and other crude oil based vehicle fuels by 2050. Then, nationwide 100% sustainable and renewable energy will be used and at least 95% of GHG emissions will be cut back. In 2004, the annual vehicle tax for methane vehicles was removed, which leads to a possible market for biomethane and natural gas. After that, more upgrading plants and filling stations were built.

7.3 Challenges

Although the general development of biomethane is optimistic, there are still challenges to be considered. The starting point of biomethane development in Finland is poor due to the historical and political preference for gasoline and diesel. Since 1965, very strong tax subsidies were used to support these conventional crude oil based fuels rather than renewable fuels. According to Lampinen, A. (2012, p.25), 10000 € of annual vehicle tax was exerted to car owners who were able to use renewable energy sources such as biomethane, NG, LPG and hydrogen as fuel in 2003. Although some subsidies were canceled in 2004, the remaining ones are still in effect and are enough to support the utilization of gasoline and diesel. Thus, it will still take time to allow the rise of an alternative methane fuels market.

It is also important to establish a uniform payment standard. Nowadays, there are six companies in Finland selling biomethane but with three different payment methods. In filling stations operated by Jeppo Biogas, Haminan Energia and Joustan Ekokaasu, only credit cards can be used. Only private billing cards are used in filling stations operated by Envor Biotech and Gasum. Metener supports cash or private billing card payment. If one payment standard is created in all filling stations, the transaction will be eased and thus, the business can be boosted. (Aittamaa, T., 2014)

The most discussed challenge is the topic of feedstock supply. Due to the lack of information, a general concern of the public is that the use of food as energy source could raise the food prices and cause great pressure. Therefore, protests by residents would cause delays on biomethane development (Junginger, M., & Baxter, D., 2014, pp.43-44). However, as mentioned earlier in the text, the production of biogas and biomethane is a treatment method of organic waste substances than using only food as feedstock. A solution to this problem could be creating public promotions and campaigns to spread the message. Meanwhile, in order to expand the biomethane capacity, new possible feedstock sources should be found, for example algae. Algae have a great methane potential, but its cultivation and utilization has mainly been done for the interest of biodiesel production. According to Kristian Spilling, a researcher in Finnish Environment Institute (SYKE), there is a Swedish project called SUBMARINER doing an ongoing project to harvest algae from the Baltic Sea. However, Finnish parties are not widely involved in it (Spilling, 2015). Thus, it is crucial to establish collaboration between biogas plants and wastewater treatment plants or even municipalities on algae feasibility research in specific cases in order to achieve sustainable biomethane utilization.

8 Conclusion

In general, biomethane is attractive to act as an alternative fuel that could support the transition of fossil fuels and targets on climate change. It has great possibility to be integrated into the current energy system in regions with good natural gas pipelines. Political decisions also stand by the use of renewable energy. Thus, there are clear trends on biomethane market growth. Moreover, it even has the opportunity to replace natural gas and eventually cut all the GHG emissions. Hence, biogas upgrading is becoming more and more popular and important. The upgrading technologies have been developed through the years and have become more mature. Among all the available technologies, water scrubbing, PSA and chemical scrubbing are the most used ones in Europe. The situation and innovations changed rapidly since chemical scrubbing was under development only a few years ago.

The development of biomethane upgrading is rapidly increasing in the whole of Europe. For biogas plants that are interested in having an upgrading unit, it is strongly recommended to conduct a market research on supply chain and feasibility. Meanwhile, new policy standards should be implemented in order to carry on the future development of the biomethane market.

This thesis topic is truly worth researching, since the biomethane market in Finland is not mature enough. By reviewing a large amount of valuable literature including governmental plans and reports, a knowledge of biomethane upgrading and its potential has been acquired. This is the biggest gain of the work. Moreover, the results lead to an expectation of more biomethane utilization in the transport sector in Finland and even in Europe, although it might still take time to alter public willingness of using biomethane as fuel and to change the structure in the transport sector. This thesis work might not be perfect enough to cover every detail of the development of the biomethane economy. It still acts as a basis for interested parties, which is also one of the main ideas of the work. If further market research and development are to be done, this thesis report could provide reference material.

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Appendix 1 – A comparison of different technologies

Parameters	Water Scrubber	PSA	Membrane Separation	Chemical Scrubber	Organic Physical Scrubber	Source
Electricity Consumption (kWh/Nm^3 biogas)	0.23-0.3	0.2-0.3	0.2-0.3	0.12-0.14	0.2-0.28	(Bauer, F. et al., 2013a, p.51)
	< 0.25	0.25	N.A.	< 0.15	0.24-0.33	(Petersson, A., & Wellinger, A., 2009, p.13)
Heat Consumption (kWh/Nm^3 biogas)	None	None	None	0.5-0.6	Internal	(Bauer, F. et al., 2013a, p.51), (Junginger, M., & Baxter, D. 2014. p.19)
Working pressure (bar)	4-7	4-7	N.A.	No pressure	4-7	(Petersson, A., & Wellinger, A., 2009, p.13)
CH_4 Content (%)	96-98	96-98	96-98	96-99	96-98	(Junginger, M., & Baxter, D., 2014, p.19)
	> 97	95-98	>96	>99	>97	(Ryckebosch et al., 2011, p.1640)
H_2S removal	Yes	External	External	External/ Yes	External	(Junginger, M., & Baxter, D. 2014. p.19)
H_2O removal	External	Yes	Yes	External	External	(Junginger, M., & Baxter, D. 2014. p.19)
CH_4 loss (%)	2	2	0.5-20	0.04	4	(Vienna University of technology, 2012, p.13)
	< 2	< 10	N.A.	< 0.1	2-4	(Petersson, A., & Wellinger, A., 2009, p.13)
	1	3.5	13.5	0.1	4	(Starr, K. et al., 2012, p.995)
Annual maintenance cost (% of investment cost)	2-3	2-3	3-4	2-3	2-3	(Junginger, M., & Baxter, D. 2014. p.19)
€/Nm^3 biomethane	0.13	0.25	0.12-0.22	0.17-0.28	N.A.	(Korres, N. et al., 2013, p.175)
Market share in Europe (%)	41	21	10	22	6	(Junginger, M., & Baxter, D. 2014. p.20)

Appendix 2 – Finland upgrading plants list

Operator	Place	Feedstock	Utilization	CH_4 content (%)	Technology	Plant capacity (Nm^3/h raw gas)	In operation since
Gasum	Espoo	sewage sludge	vehicle fuel		water scrubber	750	2012
Envor Biotech	Forssa	biowaste	vehicle fuel	97–98	membrane seperatation	16	2013
HAI/ Metaenergia	Haapajärvi	agricultural	vehicle fuel		water scrubber	10	2012
Kalmari farm	Laukaa	cow manure, fat, confectionary by-products	vehicle fuel	97	water scrubber	50	2002
Gasum	Kouvola	sewage sludge, biowaste, sludge, energy crops	gas grid	>95	water scrubber	300	2011
Joustan Ekokaasu	Jousta	biowaste, sludge, fats	vehicle fuel		water scrubber	60	2014
Jeppo Biogas	Nykarleby	pig slurry, agricultural	vehicle fuel	99	water scrubber	400	2014
Gasum	Lahti	biowaste	gas grid		water scrubber	1100	2014
Kalmari farm	Laukaa		vehicle fuel		water scrubber	60	2014